

Gain control... goes silicon

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If you think circuit gain adjustment is just an annoying artifact from the predigital era, think again. A properly ranged signal is still necessary for maximizing system S/N ratio, for matching source and load, and for reducing error rates and distortion. Many systems need gain or parameter adjustment for a variety of functions—from controlling volume, screen brightness, and filter settings to automatically maintaining system performance during changing conditions.

The implementation of gain control has changed, however. Traditional mechanical trimming potentiometers face a strong challenge from their silicon equivalent, digital, or electronic, trimmers. Digital trimmers offer flexibility, reliability, freedom from mechanical hysteresis, and compactness compared to their electro-mechanical predecessors. But, differences among vendors in internal architecture, specifications, and interfacing make it difficult to choose the "best" device for your application (see Table 1).

Also, applying an active component to replace a passive trimming potentiometer is not a simple swap. The digital trim also involves a new set of parameters, including volatility, power-handling, and noise. As a result, you may want to delay jumping on the digital bandwagon. Consider alternative approaches, such as mechanical trimmers (see box, "Don't ignore the

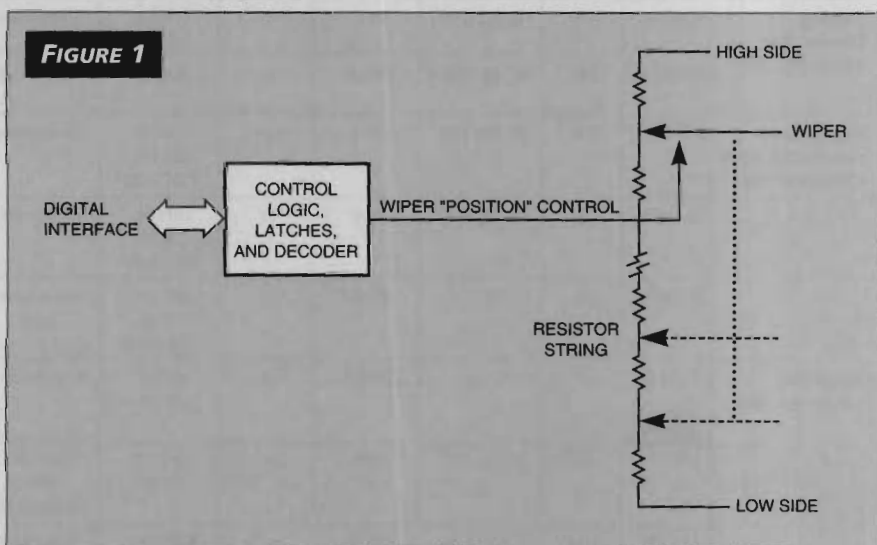
Increasingly, ICs are replacing mechanical potentiometers for gain control, providing both flexibility and compactness. However, you must choose carefully from among available architectures. Incompatibilities, limitations, and unique architectures complicate the final choice.

mechanical trimmer") and multiplying DACs (see box, "MDACs: another alternative").

Fortunately, electronic trimming via digital pots opens new approaches to solving traditional calibration issues. You can perform automated system calibration, both on power-up and during system operation. But you should also view calibration and

adjustment in a new light, because digital pots provide more—and more accessible—adjustment points than do mechanical devices. If you use digital devices to their maximum potential, you can put "operator adjustment," "opportunity for misadjustment," and "excessive tweaking" on your list of former problems.

The core of a digital pot comprises a



A digital pot comprises a string of resistors with FET switches, controlled by onboard logic and decoders, between each resistor pair.

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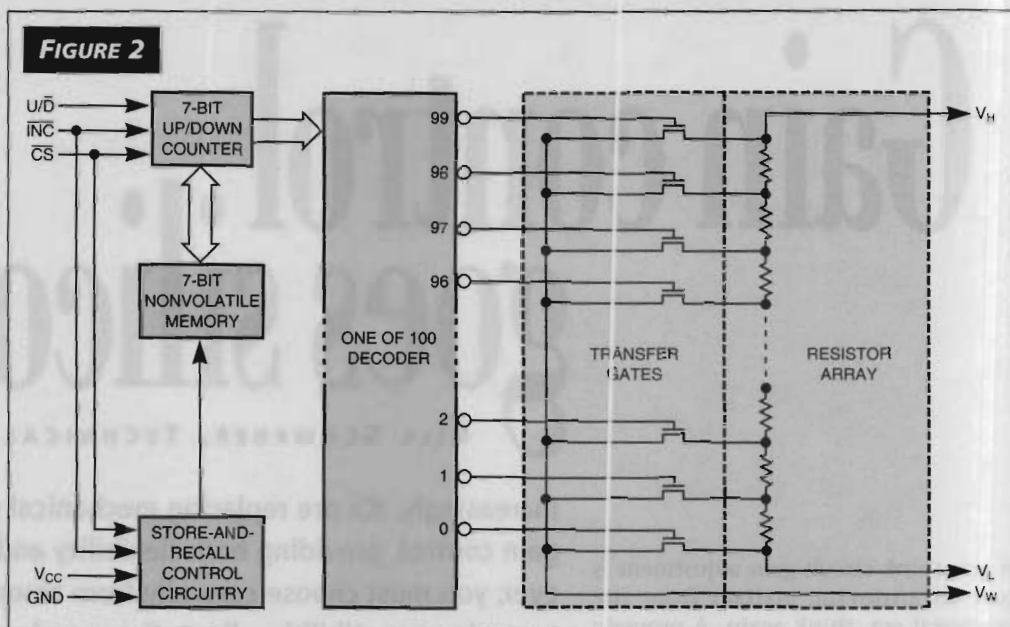
series string of resistors, with the connections between resistors tapped to a wiper via an FET switch (Fig 1). Relatively simple control logic manages the necessary switching. As you turn the switches on and off, you observe the same effect as that of a wiper's changing resistor positions or turns to reach a desired tap.

Digital pots offer some obvious advantages over mechanical trimmers. For example, the digital devices lack moving parts and offer greater mechanical ruggedness and vibration resistance. They come in standard DIP or surface-mount IC packages, and you can install them with standard equipment and handle them as you would any other IC. The advantages go beyond the basic package and ruggedness, however. Digital pots are available in 2-mm-high

packages, making them compatible with low-profile formats, such as PCMCIA Type I cards. In addition, 1-mm-high TSSOPs will be available soon. Sin-

gle, dual, and quad digital pots in a single package also make maximum use of limited pc-board space.

Digital pots also change the way you



Xicor's nonvolatile X9312, with 99 resistors (100 positions), has three control lines: an up/down line for setting increment direction, a line for stepping, and a chip select.

TABLE 1—REPRESENTATIVE DIGITAL POTENTIOMETERS

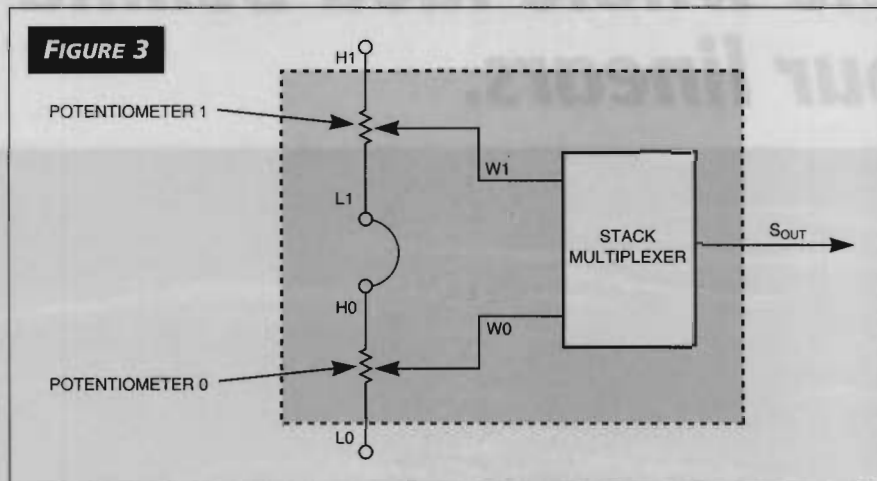
Company	Model	Steps	Resistance (k Ω)	Configuration	Non-volatile	Packages	Interface	Operating power	Features	Price (1000)
Analog Devices Inc Circle No. 301	AD8402	256	10, 50, 100	Dual	No	DIP-14, SO-14	Three-wire	2.7 to 5.5V, 5 μ A	Full ac specs, nA shutdown current	\$1.66
	AD8403	256	10, 50, 100	Quad	No	SOL-24	Three-wire	2.7 to 5.5V, 5 μ A	Full ac specs, nA shutdown current	\$2.51
Dallas Semiconductor Corp Circle No. 302	DS1267	256	10, 50, 100	Dual	No	DIP-14, SO-16, TSSOP-20	Three-wire	5 or $\pm$ 5V, 650 μ A	Stackable wipers for 512-step resolution	\$2.45
	DS1867	256	10, 50, 100	Dual	Yes	DIP-14, SO-16, TSSOP-20	Three-wire	5 or $\pm$ 5V, 650 μ A	Nonvolatile version of DS1267	\$3.14
	DS1802	64	50	Dual	No	DIP-20, SO-20, TSSOP-20	Three-wire and pushbutton	3 or 5V, 2 mA	Log taper, mute, audio specs	\$2.56
Xicor Inc Circle No. 306	X9511	32	1, 10	Single	Yes	DIP-8, SO-8	Pushbutton	5V, 3 mA, 200 μ A standby	Auto-store or user-store wiper, X9514 is a log-taper version	\$0.85
	X9221	64	2, 10, 50	Dual	Yes	DIP-20, SO-20	Two-wire (I ² C-compatible)	5V, 2 mA, 500 μ A standby	Multiple wiper settings, can be cascaded	\$2.80
	X9312	100	1, 2, 10, 50	Single	Yes	DIP-8, SO-8	Three-wire	5V, 3 mA	Up to 0 to 15V across terminals, up/down, clock select 1-mA shutdown	\$1.45

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design trims into a circuit. A traditional approach groups multiple trims at one board edge for convenient operator access, except what is convenient or necessary for an operator often degrades circuit performance and takes up board space. With digital pots, instead of placing the trim to ensure reasonable access for the person doing the trimming, you can place the trim close to its associated circuit. This approach yields better signal-integrity maintenance, reduced noise pickup, and reduced use of the board space a mechanical trim requires to run tracks to remote trims.

The direct approach to using a digital pot to replace a mechanical potentiometer is on a one-for-one basis. Before you do that, carefully study the specs of these active devices to see how they differ from mechanical trimmers. Equally important, think about how you use trims to see if using a software-controllable trim changes the way you achieve your performance goal in the circuit.

For example, you no longer need compromise the performance to avoid complex or iterative trim sequences. Unlike a test operator or technician, these sequences don't irritate the algorithm that controls them. Similarly, you need not reduce trim-adjustment locations solely to reduce operator test and trim time if an extra trim would



The DS1287 (and nonvolatile DS1867) features an internal multiplexer so that its two channels can be "stacked" to provide twice the resolution of either channel.

provide performance benefit. You can design a circuit that will more easily tolerate system test and calibration on the production floor. Finally, the ability to trim and set gain, offset, and operating points during circuit operation means that you can design a circuit that adapts to changing conditions and configures itself under software control for best performance in the signal path.

Not drop-in replacements

Digital pots need power to operate, so you must consider some complex issues, such as how they retain and

restore wiper settings when you remove and reapply power. Vendors offer various solutions. For example, the 100-step Xicor X9312 digital pot has built-in nonvolatile, electrically erasable memory (Fig 2). You can set the device to retain the last wiper position when you remove power and restore it when you apply power. Alternatively, you can set the device to power up to a preset value. This approach would suit applications in which the device controls audio volume, for example, so that sound level doesn't come up at full blast when you restore power. Similar-

DON'T IGNORE THE MECHANICAL TRIMMER

Mechanical trimming potentiometers, available from such vendors as Bourns and Spectrol, have served circuit designers well for decades. A single-turn pot provides resolution, which differs from repeatability, of about 0.05%, or one in 200 parts; multiturn pots offer greater resolution. Before you rush out to replace a trimmer with a digital pot, consider some of the virtues of this old friend.

For example, trimmers come in a range of values from a few ohms to megohms, and their power-handling capabilities are limited only by how much space your circuit has. They also provide flexibility: You can easily change your design's installed resistance value. Further, mechanical trimmers can withstand greater overloads and common-mode voltages than do digital pots; the circuit supply voltage puts less constraint on the mechanical devices' signal level.

In addition, because of their lower parasitic capacitance, mechanical trimmers generally have wider bandwidths than

do digital pots. You can also adjust mechanical trimmers without operating-system software, drivers, or debuggers. All you need do is apply power and signal to your circuit and monitor a test point with appropriate equipment, such as a scope or meter. This approach is convenient for adjusting an analog-signal chain for gain/offset/range parameters or for setting up an analog filter.

By measuring resistance with a meter, you can easily determine whether a mechanical trimmer is working properly. You need no applied power or software. In addition, you need not worry about your software's changing a setting that you want set for the lifetime of the equipment. Also, application software does not have to manage settings.

Unlike digital pots, nearly every mechanical device is available from several second sources. Finally, because trimmers are nonvolatile, they avoid all the power-on and write-cycle issues of digital pots.

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ly, the Analog Devices AD8402 series and the Dallas Semiconductor DS1668 series power up at vendor-preset positions.

Not all applications require non-volatile storage of the wiper setting. To meet these needs, Dallas Semiconductor offers both volatile and nonvolatile devices; for example, the DS1867 is the nonvolatile version of the DS1267 256-position dual digital pot. Analog Devices minimizes digital pot complexity and cost by assuming that you can use some other nonvolatile memory in your system.

As always, you must make the trade-offs in component cost, allocation of power-up functions (system software vs the IC's transparent internal memory), and desired power-up condition (using the last pot setting, a software-defined value, or a trimmer-defined neutral, or midscale, setting). For digital pots without internal memory, consider the implications on your production or field-test operation when you store the trimmer setting in a component that is physically separate from the trimmer IC.

Consider the application and the number of times the setting of the trimmer will change and, thus, require storage. The EEPROMs in digital pots perform 50,000 to 100,000 writes, probably enough for most applications, and data retention is more than 100 years—well beyond the equipment's lifetime.

Vendors and models offer different approaches to how and when to store the pot settings—another source of potential confusion and functional incompatibility. You can set the Xicor X9511 to store the current setting whenever you remove power; you can also set the device to store any changes in wiper setting as they occur. The Dallas Semiconductor DS1869 uses a different approach: It automatically stores a new setting if the change is greater than 12.5% of the total resistance range.

Also, consider what you want to happen if you shut down power while the wiper position is changing. Should the memory retain the last "valid" position (when a time-out indicates that the

wiper has stopped moving), or could you inadvertently show some indeterminate value? Finally, watch how your power supply drops when you remove power. For the EEPROM to automatically store on power-down, the rail must drop slowly enough so that there is time to both sense the drop and to perform the write cycle. Carefully check the data sheets and your design to ensure that the power-supply drop-off rate meets the specification.

Pick a value, but not any value

Unlike mechanical trimming pots, digital pots don't offer a large span of full-scale-resistance values. You must properly scale your associated circuitry to make maximum use of a digital pot's values. All vendors offer 10-, 50- and 100-k Ω nominal values; Xicor also offers some 1- and 2-k Ω units.

You must also consider resolution. Vendors specify digital pots by the number of distinct positions, or taps, they provide. This number ranges from 32 to 256, and some devices, such as the Dallas DS1287 or DS1867, can cascade,

MDACs: ANOTHER ALTERNATIVE

Multiplying DACs (MDACs) are functionally similar to digital pots, providing a usually buffered output current or voltage equal to the input signal multiplied, or weighed, by the digital setting of the DAC input. Rather than a series string of switched-in resistors, however, MDACs use R-2R ladders to assign weights on the input signal. MDACs take a variable static or dynamic external analog signal as their reference instead of using a fixed reference value to the R-2R ladder. Most MDACs buffer the input as well.

MDACs can support either two-quadrant multiplication, with the input spanning from negative to positive and the control signal positive only, or four-quadrant multiplication, with the input and control both spanning negative to positive. MDACs offer resolutions of 8, 12, 14, and even 16 bits. Traditionally, MDACs were available only with parallel interfaces, but many new units feature serial interfaces for smaller package size, as well two, four, and eight channels in a single IC. Most MDACs let you set the output buffer to provide gain and attenuation.

As voltage- or current-output devices, MDACs would not suit an application requiring variable resistance. However, you may consider them for applications controlling or setting a voltage or current value. These applications include controlling programmable power supplies, establishing dc or bias conditions for op amps, adjusting digitally controlled analog

filters, and setting gain or power levels for amplifiers, as well as providing comparator setpoints in automatic test equipment.

Application-specific MDACs for high-fidelity-audio volume control provide such features as stereo operation (two linked channels), panning (increasing one channel's gain while reducing the companion channel's gain), muting, tone (treble and bass), and balance. These MDACs cover the audio bandwidth. For example, the TDA7312 from SGS-Thomson Microelectronics lets you choose one of four stereo-input channels, control in 1.25-dB/step, and control via the I²C bus μ P interface. National Semiconductor's LM1972, an audio-specific, dual R-2R resistor string offers 70-dB attenuation (0.5-dB steps from 0- to 47.5-dB attenuation and 1-dB steps from 48 to 104 dB, along with mute. You control the device with a three-wire serial interface that you can daisy-chain to as many ICs as necessary.

Other MDACs, such as the Maxim MAX532, are 12-bit devices for dc-level setting, which you can use for controlling programmable power supplies and in other test applications. These devices emphasize dc specs, such as integral nonlinearity, gain TC, settling time, and guaranteed monotonicity over temperature. However, some, such as the AD7845, also provide ac specs, including full- and small-signal bandwidth, along with THD.

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or stack, digital pots to achieve greater resolution, with 256 taps achieving approximately 0.4% resolution (Fig 3). But many applications, such as setting screen brightness or adjusting an analog signal-path gain range, don't require high resolution, and 32 taps may be enough.

The steps between taps also need not be linear. Both Xicor and Dallas offer log steps for applications, such as audio volume, having wide dynamic ranges in the signal. The Dallas Semiconductor DS1802 features 64 steps with 1-dB/step log taper; the Xicor X9514 has 32 log steps.

Just as with any other pot, you can use these digital pots in two modes: three-terminal, voltage-dividing, or ratiometric, potentiometer mode or two-terminal, simple-resistor, rheostat mode. When using the pots as a rheostat, tolerance from nominal can reach 20%. However, many applications, especially those using the pots as voltage dividers, don't require low tolerance.

Designing with digital pots also offers good channel-to-channel matching on multiple-channel devices. For example, the Analog Devices AD8402 family has 1% matching. Digital devices also provide good matching temperature coefficients: Although rheostat's temperature coefficients of resistance (TCRs) can reach 500

ppm/°C, those of resistive dividers can be as low as 15 ppm/°C.

Setting the values you want

You can set a digital pot's value through a processor interface or a "switch-closure" interface. Processor interfaces are serial to minimize interconnection requirements for clock, data, and chip select. Interfaces and timing differ, however, reducing your design's ability to accommodate multiple sources. Maximum clock rates range from 1 to 10 MHz, so you must provide a corresponding clock in your system.

Most digital pots use internal, non-volatile memory as "shadow" memory, which transparently saves new settings by sensing the power-down transition. Others use the system processor to write to an EEPROM register, which, in turn, controls the wiper; this approach has more complex system timing and protocol requirements. Some Xicor devices support a bidirectional master/slave protocol over the serial data line. In this approach, the digital pot acts as a slave to acknowledge handshaking to the master CPU to verify that it received valid data.

Serial interfaces can be absolute-position or up/down versions. In absolute-position interfaces, you load a word with the desired wiper-position number. In up/down interfaces, you select up or down mode and issue pulses to

step the wiper through succeeding positions. Digital pots having multiple channels on one IC reserve extra data bits to indicate which internal channel is being addressed.

You can daisy-chain some serial absolute-position devices via a data-out signal connected to the data in the signal of the next device. This lets you control a virtually unlimited number of pots via just three wires, and double-buffered latches prevent the pots from responding to transitional data bits.

However, a processor algorithm does not make all trims and adjustments in a circuit. For example, users typically set screen brightness and volume control. In these cases, you may not want to involve a processor in the adjustment loop such that the processor would have to interpret a user's finger action and send a corresponding command to the affected part of the circuit.

Switch-closure interfaces suit applications, such as volume, brightness, and temperature control, requiring hands-on adjustment. In these applications, changing the resistor value directly affects the final signal you want to control, independent of a processor action or software. Both Dallas Semiconductor and Xicor offer units with debounced lines for the up and down pushbutton connections. The Xicor X9511 PushPot and its log-taper sibling, the X9514, exemplify digital pots that let users directly set a value via two pushbuttons.

Consider what your design can tolerate while a wiper is changing. Because digital pots include on/off switches that connect each resistive element, consider what happens if one switch makes or breaks before the next switch breaks or makes. Momentary glitches occur when the apparent resistance value suddenly makes a large step before settling to the desired value. Again, this consideration may be irrelevant in such applications as brightness control. However, in other applications, such as channel gain ranging, such glitches can cause signal overrange and input saturation, which you must accommodate via suitable timing. Some new devices, such as the Analog Devices AD8402 series, contain circuitry to minimize any glitches inherent in

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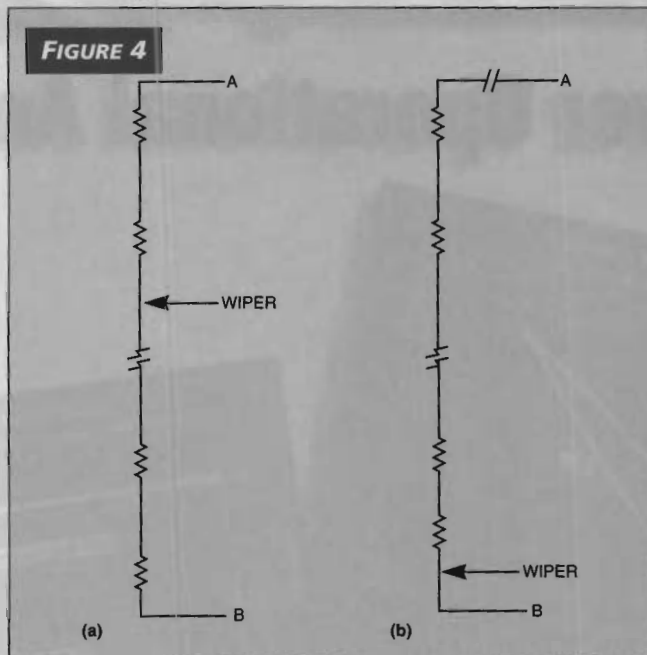
switched-resistor designs. The Dallas Semiconductor DS1801 for audio features zero-crossing detection circuitry, which eliminates "zipper" noise by allowing the wiper to move only during moments of no audible signal.

The trend toward lower voltages and power has reached these digital components. Some devices operate on single 3 to 5V supply; others, on dual $\pm 3V$ supplies. Current consumption in active mode has dropped from 10s of milliamps to just a few milliamps.

Some new devices consume just a few microamps when in shutdown or standby mode, which differs from power-off mode. For example, you can put the AD8402 series (Fig 4) into shutdown mode via a control pin. The pin makes the device open one of its internal resistor-string-end terminals while shorting the wiper to the other terminal and while retaining the wiper setting in internal latches for use when leaving shutdown mode. As a result, the only current consumption is a 5- μA leakage in the resistance string.

Typically, you need not worry about a mechanical trimmer's wiper. With digital pots, though, you must limit wiper current to less than 1 mA. You must also consider wiper resistance, which can range from 40 Ω to several hundred ohms. Higher wiper resistance reduces temperature stability and bandwidths.

You must also limit the applied signal span. Typically, you have to keep the maximum analog signal across the ends of the resistor string within the supply voltage, with a little extra head room. Xicor's X9312 allows 0 to 15V across its terminals from a 5V supply. Applied signal span can be a problem if your system has transients or if you don't have complete control over the applied signal, such as one from an external source.



In shutdown mode (a), the resistor output of Analog Devices' AD8402 changes from the power-on position to one terminal open (b), with the wiper shorted to the other terminal, while retaining the actual setting in latches.

Specs make a difference

Digital pots are functionally simple, but, like all other components, they have subtle performance specifications. Unfortunately, differences in vendors' internal architectures, interfaces, and approaches mean that data-sheet formats and specs have little in common. Some concentrate on digital control and timing; others emphasize analog performance through the resistor string. You must carefully examine such specs as bandwidth, linearity and distortion, dynamic signal handling, crosstalk, and internally generated noise, for example.

Bandwidth ranges from audio frequencies to about 1 MHz. For example, the 1-k Ω Xicor XC102 in rheostat mode has a 1.8-MHz, -3-dB point. However, RC time constants largely determine bandwidth, and the 10-k Ω family member has a 30-kHz bandwidth. In contrast, the 10-k Ω AD8402 features 600-kHz bandwidth. Some devices suit audio volume controls, providing flat response and full specs over the 20-kHz audio band.

Linearity and distortion are important in such applications as audio sig-

nals and critical open-loop settings. A well-designed device can provide internal noise level and differential nonlinearity comparable to those of D/A converters: 2 and 1 LSB, max, respectively. Similarly, several models offer distortion below 0.010% for the audio band.

Carefully check the specs for dynamic signal handling. Again, this feature is not important in digital pots in level-setting applications, such as brightness, but is necessary in those applications in which the digital pot must pass ac signals.

Not all devices have a crosstalk spec. Crosstalk between channels in multiple channel devices is typically -60 dB or better.

The resistive elements and wiper resistance contribute to internally generated noise, which may be significant at

high bandwidths switching in lower position resistors in the string.

Careful attention to these specs will affect the success of your design: Pay attention beforehand so you won't waste time—and money—with the wrong device.

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